

NUMERICAL INVESTIGATION OF THE DROP FORMATION MECHANISM AND STUDY OF THE DROPLET'S PRESSURE CONTOUR

PARDEEP¹ & M. K. SINHA²

¹Research Scholar, Department of Mechanical Engineering, NIT Jamshedpur, India

²Associate Professor, Department of Mechanical Engineering, NIT Jamshedpur, India

ABSTRACT

The current study provides the numerical investigation of the drop formation mechanism. Volume of fluid methods is used for the numerical simulation. The analysis contains 2% Polyacrylamide as the main fluid that dispersed in the air. For analyzing the drop mechanism, the Velocity Vector Contours are studied. Velocity contours also explain the phenomenon of the satellite drop formation process. Pressure Contours demonstrate the variation of pressure in the drop at various time steps. Pressure varies exponentially at the necking zone for each step of the drop formation. The variation of velocity at the leading edge of the drop is also investigated. The magnitude of the velocity decreases during the neck formation, because the liquid upside and downside the necking point tugs one another towards their side.

KEYWORDS: Pressure Contour, Non-Newtonian, Volume of Fluid & Velocity Vector

Received: Nov 26, 2017; **Accepted:** Dec 16, 2017; **Published:** Jan 05, 2018; **Paper Id.:** IJMPERDFEB201833

INTRODUCTION

Development of drop fascinates a lot of researchers due to its wide applications. Drop development in a falling stream of fluid has been a subject of much research from the beginnings of the hydrodynamic theories. A number of authors introduced various theories in investigating the physics behind the drop formation. In the 19th century, the wonder was depicted by Rayleigh. Rayleigh concentrated on perturbations of various wavelengths and computed their development rates. Albeit long wavelength perturbations tend to frame bigger drops with the smallest surface area, and substantial mass transport between the drops is required. In 1833, F. Savart examined the putrefaction of a liquid jet by enlightening the jet with sheets of light. He watched undulations developing on a jet of water that causes the breaking of the jet and resulting drop development. The advancement of photography and the late utilization of PCs gave us a new capacity to imagine the flow of drop arrangement.

Disentangled details of the Navier-Stokes equations for an incompressible stream with a free surface have been delivered in various reviews with an end goal to comprehend the physical systems administering the drop development. Various algorithms are used to predict the profile of the drop formation. Wilkes et al. (1999) did the numerical investigation of drop formation through the capillary tube into ambient air by making Finite Element Algorithm which indicates a great understanding of his experimental work. Likewise, Zhang and Stone (1997) dropped arrangement at the tip of a vertical, and round narrow tube inundated in a moment immiscible liquid is considered numerically for low-Reynolds-number streams utilising the Boundary Integral Method. Zhang (1999) developed a model to predict the evolution of drop shape and its breakup from the tip of vertical, circular tube into ambient air based on Volume-of-fluid/Continuum Surface Force method. A model is developed by Zhang (1999)

to predict the evolution of drop shape and its breakup based on RIPPLE, which is a solution algorithm for computing transient, incompressible fluid flow in two-dimensional with the surface tension of the free surface of general topology.

Kryukova et al. (2015) experimentally investigated the impact of different physical parameters on the dispersion of liquids. According to him, surface tension is one of the influencing parameters that affect the size distribution of the drops. Castrejón-Pita et al. (2012) examined that the surface tension drives two contending forms, squeezing off and shortening, and the relative timescales of these, controlled by the harmony amongst slender and gooey powers, decide the ultimate result. Wehking et al. (2014) studied the impact of interfacial tension between the two immiscible fluids, viscosity ratios, and channel geometries on droplet formation. According to them, the transition flow rate ratio (Q dispersed / Q continuous) for a given capillary number declines with declining aspect ratio for both DTJ–DC and DC–PF transitions. Pericet-Camara et al. (2008) revealed that the stresses of a sessile droplet on an elastic surface due to its capillary pressure inside the drop and surface tension at the periphery of the drop create a characteristic deformation profile with a crater-like shape. This experimental profile is imaged and authenticates with the theoretical predictions available by continuum elastic theory. It is detected that the surface deformation increases for lower values of Young's modulus of bulk polydimethylsiloxane (PDMS). Also, it is confirmed that the drop size has no effect on depth of the depression. Beyond the experimental work, nowadays different numerical methods are used to examine the drop formation process. Dravid V et al. (2008) observed the process of satellite drop formation and determine the conditions which required in controlling the diameter of drops. The Galerkin finite element approach is used to solve the governing equation. Pan Y. and Suga K. (2003) investigates the pinch-off process of drop liquid into another liquid in a three-dimensional model. The level set method is used for the tracking of the complete pinch-off process. Yuriko Renardy and Michael Renardy (2002) develop an accurate representation of the body forces generated through surface tension and named it as the parabolic reconstruction of surface tension (PROST). Volume of fluid method is used for the solution of Navier-Stokes equation. Fawehinmi O. B. et al. (2005) studies the effect of flow rate and viscosity on the drop dynamic process through experiments and CFD packages i.e. CFX and FLOW 3-D. Pardeep et al. (2016) studied the impact of flow rate variation on the development of satellite drop formation. Through numerical simulation, it was revealed that effect of velocity is less on smaller size capillary tube as compared to the bigger sized tubes.

The objective of this work is to study the detachment process velocity variation with the simulation time and also investigate the variation of pressure inside the domain of drop during the dynamics of drop formation by using Computational fluid dynamics (CFD) tool.

COMPUTATIONAL SIMULATION OF CAPILLARY TUBE

Computational fluid dynamics is one of the important subjects of fluid mechanics to determine the live fluid problems. CFD uses the numerical methods and various algorithms to solve the physical fluid flow problems. It reduces the cost of experimental setup that may be installed for the purpose of solving the problem.

RHEOLOGICAL PROPERTIES

Polyacrylamide (PAA) is used as the main fluid for the drop formation process. Physical properties of 2 % PAA is given in Table 1. The flow behaviour of 2 % PAA is Non-Newtonian.

Table 1: Physical property of 2% PAA [Joseph et al. (1999)]

Liquid	Viscosity(kg/ms)	Surface Tension(N/m)	Density(kg/m ³)
2 % PAA(2% Polyacrylamide)	0.96	0.045	990

MODELING OF PHYSICAL DOMAIN

Figure 1 shows the geometric model of the computational domain developed in the ANSYS-FLUENT module. Initially the computational domain is validated with the literature results within the applied boundary conditions [16]. The green shaded region shows the viscoelastic fluid named 2% polyacrylamide (PAA) aqueous solution, whereas the grey shaded region is an air chamber.

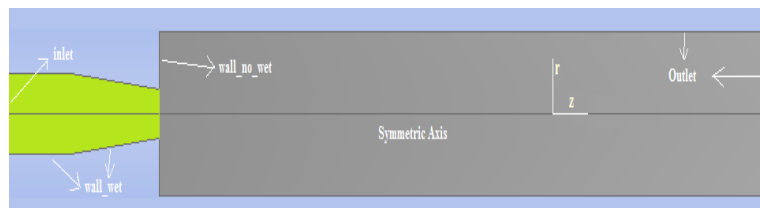


Figure 1: Physical Computational Domain

BOUNDARY CONDITION AND SOLUTION PARAMETERS

To examine the drop dynamics process, 'Volume of Fluid' model is used. Volume of Fluid method is used to locate the drop's profile during its detachment process. To initiate the ejection process, a velocity user-defined function (UDF) is intercepted with the VOF model. The whole process takes places under the atmospheric pressure conditions.

Assumptions

- The computational model is axisymmetric.
- The incompressible property is considered for the surrounding air.
- The physical properties of the liquid are known and constant.
- Evaporation phenomenon for the liquid is neglected.
- At the inlet of the capillary tube, fluid flow is assumed to be fully developed flow.
- The thickness of the capillary tube exit is neglected [2].

The boundary condition used for the computation is marked in Figure 1 and also stated as

- Inlet of the domain is velocity inlet.
- Axis is considered as an axisymmetric axis.
- Free slip velocity condition near the wall because the fluid near the wall is air.
- The outlet of the computational domain is an atmospheric pressure outlet.

MATHEMATICAL MODELING

On the basis of assumptions, the Navier-Stokes Equation in non-dimensional form for the transient motion of the

liquid is considered as,

$$\nabla \cdot \mathbf{v} = 0, \quad (1)$$

$$\text{Re} \left(\frac{\partial \mathbf{v}}{\partial t} + \mathbf{v} \cdot \nabla \mathbf{v} \right) = \nabla \cdot \boldsymbol{\tau} + \left(\frac{\rho}{\rho_0} \right) \mathbf{j} \quad (2)$$

$$\boldsymbol{\tau} = -p\mathbf{I} + [\nabla \mathbf{v} + (\nabla \mathbf{v})^T] \quad (3)$$

The variable in equation (1) i.e. ∇ is the gradient operator; \mathbf{v} is the resultant velocity vector. Similarly in equation (2), $\boldsymbol{\tau}$ is the stress tensor; \mathbf{j} is the unit vector in the z-direction. In equation (3), p represents the dimensionless pressure and \mathbf{I} is the identity tensor.

Also during the non-dimensionalization process, three dimensionless numbers are introduced in equation (2),

Reynolds number, $\text{Re} = \rho U D / \mu$,

Gravitational Bond number, $G = \rho g R^2 / \sigma$,

Capillary number, $\text{Ca} = \mu U / \sigma$

The flow is considered as fully developed, so its velocity profile become,

$$v_z = \frac{2Q}{\pi R^2} \left\{ 1 - \left(\frac{r}{R} \right)^2 \right\}, \quad 0 \leq r \leq R \quad (4)$$

Where, r is the radial coordinate of drop phase, and v_z is the flow velocity in the z-direction.

The maximum velocity of liquid phase flow for the fully developed flow is given as

$$U = \frac{2Q}{\pi R^2} \quad (5)$$

RESULTS AND DISCUSSIONS

Figure 2 demonstrates the detachment of the 2% PAA liquid in the ambient surrounding. As the fluid is viscoelastic, so the thread length is more as compared to the Newtonian fluid's length because thread length mainly depends on the viscosity of the material. Movement of fluid particles can easily be seen through the velocity vector contours. Velocity vector contour shown in Figure 2 represents the necking portion of drop detachment process. The particles of the droplets move in both directions i.e. $-z$ & z directions from the necking portion. This phenomenon also responsible for the satellite drop formation as shown in Figure 3. Development of the small drop size grooves in the thread can be visualized easily in Figure 3. These grooves finally lead into the formation of the satellite drops.

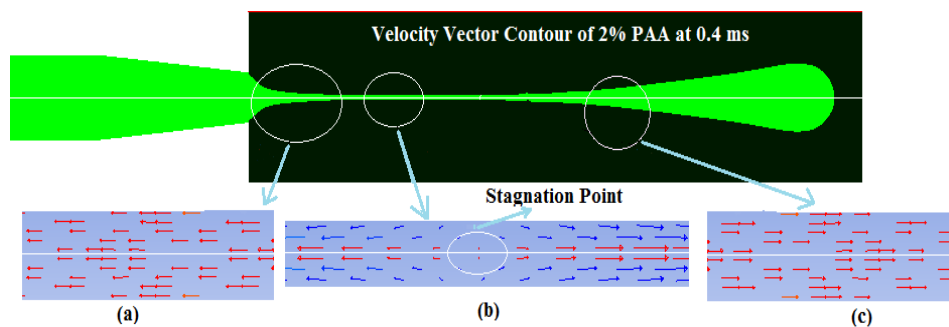


Figure 2: Velocity Vector Contours of 2% PAA at 0.4 Ms

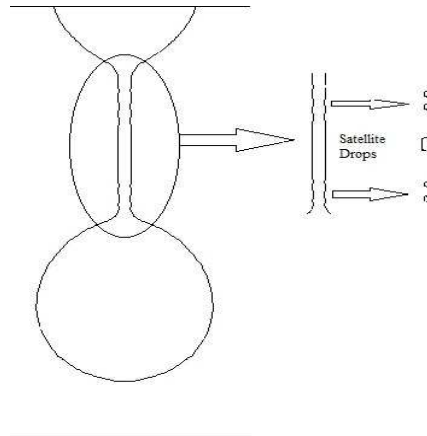


Figure 3: Satellite Drop Formation of 85% Glycerine Liquid

For a Non-Newtonian fluid, due to high viscosity value, the length of the drop detachment profile is more as compared to that of the Newtonian fluid. During the breaking period of the long thread of the droplet, a large recoil force is developed at the both ends of the liquid thread due to which a number of small drops known as Satellite drop generate. Figure 4 shows the absolute pressure contours in which pressure varies hydrostatically from inner portion towards the tip of the drop. The detachment process of drop completely depends on the weight of liquid hanging freely on the other hand, once an adequately huge measure of liquid has streamed into the drop, its base bit starts to fall quickly because of gravity; this is made apparent by the more extended lengths of the velocity vectors underneath the neck. The quick fall of the base part of the drop causes the neck to contract quickly, which develops a large pressure in the neck region as shown in Figure 4. Because of the necking, pressure gradients emerge that the liquid to evacuate the neck, as appeared in the corresponding velocity vector field plot in Figure 2. Examination of the velocity vectors field at $t = 0.4$ ms unmistakably demonstrates a stagnation point situated along the z -axis amidst the neck and fluid moving toward both the base of the drop and the end of the capillary tube's outlet.

The fluid that is flowing towards the upward direction from the stagnation point crashes into the down-flowing fluid that is being encouraged into the slim, framing an inner layer. The impact zone between the upflowing fluid and the down-flowing fluid achieves a pivotal area barely end point of the capillary tube's exit. Due to this high-pressure zone, the further inflow of liquid in the drop is terminated. As indicated by the 1-D approximation, the pressure, $p = p(z)$ and thus the pressure contours ought to be flat lines wherever inside the drop. In any case, the pressure turns into a component of r and also z inside a unit remove upstream and downstream of the hub area where the neck is tightest.

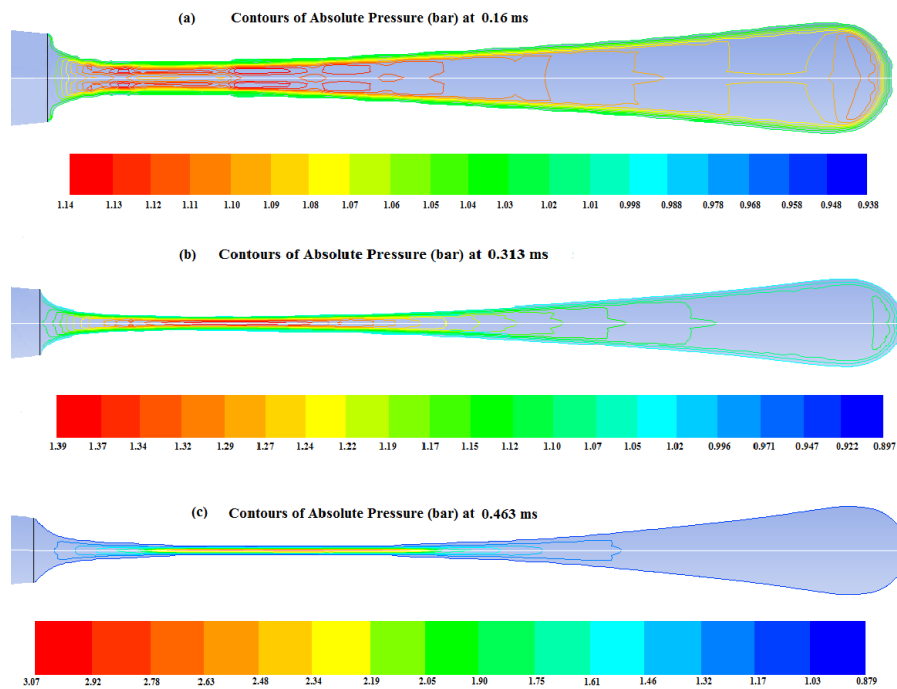


Figure 4: Contours of Pressure for (a) 0.16 ms, (b) 0.313 ms, (c) 0.463 ms

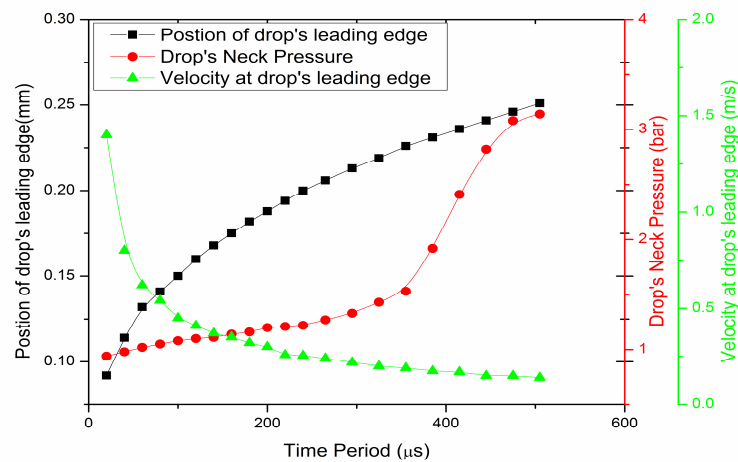


Figure 5: Variation of Drop's Neck Pressure, Velocity at Leading Edge of the Drop's Position of Drop's Leading Edge with Respect to the Time Period of the Simulation

As the drop leads towards the downward direction, i.e. z - direction, the pressure in the neck region increases gradually. Pressure in the necking region increases exponentially as the drop's reached near the break-up. The velocity of the liquid (drop's) is more during the start of the simulation. During the necking region of the drop, the liquid material moves both in $-z$ and z direction which leads the decrease in the velocity of the breakoff, because the mechanism moves towards the equilibrium.

CONCLUSIONS

In this numerical analysis, we see the ejection process of the droplet from the liquid jet. In the beginning of the

drop formation, the tip of the liquid jet converges, elongates, and creates the primary drop. The liquid bridge is developed during the elongation stage. The analysis is being done after stabilizing the Non-Newtonian liquid flow in the capillary tube. Velocity contours determine the movement of Non-Newtonian fluid within the drop volume. In the necking region, the value of pressure gradient is more as compared to the remaining part of the drop's thread. Due to this high pressure, a stagnation point develops at the weakest part of the thread. The liquid above this point pulls itself towards the capillary tube exit, whereas the downside part pulls itself towards the outlet zone. Due to these pulling forces, the liquid drop breaks up. This also results in the satellite drop formation. It is also concluded that there is a very little pressure variation which occurs in the outer part of the domain of drop also along the radial direction. Due to the development of high pressure zone at the neck region, further inflow of the liquid stops. This causes retardation in the velocity of the drop's leading edge while the simulation proceeds with time. The results of the simulation also prove the effectiveness of CFD—FLUENT module in the free surface flows.

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